

**ADDITIONAL COMPLEXITIES IN NAKHLITE PYROXENES: A PROGRESS (?) REPORT.** G. McKay<sup>1</sup>, T. Mikouchi<sup>2</sup>, and C. Schwandt<sup>3</sup>, <sup>1</sup>Mail Code KR, NASA Johnson Space Center, Houston, TX 77058, USA, [Gordon.McKay@jsc.nasa.gov](mailto:Gordon.McKay@jsc.nasa.gov), USA, <sup>2</sup>Dept. of Earth and Planetary Science, University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan, <sup>3</sup>ESCG/JSC, Houston, TX 77058.

**Introduction:** Nakhilites are olivine-bearing clinopyroxene cumulates [e.g., 1]. Based on petrographic characteristics, they may be divided into groups that cooled at different rates and may have been formed at different depths in a single flow [e.g., 2, 3]. The order of cooling rate is Lafayette < Governor Valadares ~ Nakhla < Yamato000593 < NWA817 ~ MIL03346. Nakhlite cumulus pyroxene grains consist of large cores that are nearly homogeneous in major element composition surrounded by thin rims that are zoned to Fe-rich compositions. Detailed study of these pyroxenes is important because they retain a record of the crystallization history of the nakhlite magma. Moreover, because the composition of the nakhlite parent melt cannot be directly determined, “inversion” of the major and minor element composition of the cumulate pyroxene cores can be used to estimate the composition of that melt. Thus it is important to understand the major and minor element zoning in the cumulus pyroxenes. We recently reported complications in the minor element zoning of nakhlite pyroxenes, especially for Al and Cr [4]. This abstract reports additional complications noted since that report.

**Observations:** (1) Although homogeneous in quadrilateral components, most nakhlite pyroxene cores are heterogeneous in Al content. We first reported on this heterogeneity in 1993 [5], but modern elemental mapping techniques have allowed greater insight into this phenomenon. Fig. 1 shows Al maps of two nakhilites MIL 03346 (MIL) and Y-000593 (Y593). They have fundamentally different zoning

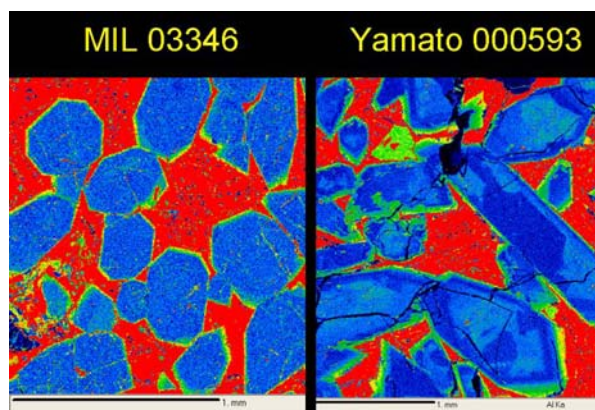


Figure 1. Al map of pyroxenes in MIL and Y593. MIL pyroxenes are fairly homogeneous in Al, while those in Y593 show patchy variation and bimodal distribution of concentrations. Bars are 1 mm.

patterns. MIL is essentially homogeneous in Al, while Y593 has patchy zoning that appears to be crystallographically controlled in some areas, but irregular in others. Such patchy zoning is typical of all but the most rapidly cooled nakhilites.

(2) Pyroxene cores of several nakhilites have a bimodal distribution of Al contents [Fig. 2]. There is a clear bimodal distribution for Y593, Nakhla (Nak), and Governor Valadares (GV), and a hint of one for Lafayette (Laf). NWA817 (NWA) has no obvious bimodal distribution, and MIL is strongly peaked at about 0.9 wt%  $\text{Al}_2\text{O}_3$ .

(3) The distribution of Al contents appears to vary systematically with inferred cooling rate. For MIL and NWA, the most rapidly cooled nakhilites, the peak of the distribution in Al content is around 9%. As cooling rate decreases, the average Al content shifts to lower values, primarily by a “flow” in the population from the high-Al mode to the low-Al mode.

(4) Core pyroxenes from most nakhilites contain tiny melt inclusions that are much more abundant in the Al-rich regions than in the Al-poor ones. Figure 3 shows images and an Al map of pyroxenes from Y593, a typical moderately-cooled nakhlite. This figure illustrates the abundant small melt inclusions that are present in the pyroxene cores of most nakhilites. These inclusions have been described previously [e.g., 1, 6, and 7]. They typically contain Si, Al-rich glass plus

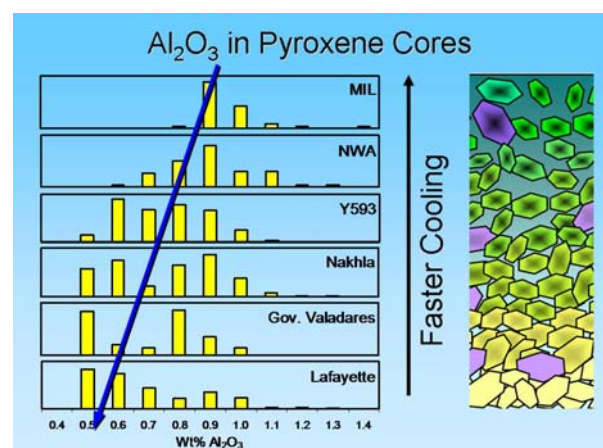


Figure 2. Histograms of core pyroxene Al contents for Nakhilites arranged in order of inferred cooling rate [3]. The blue arrow indicates the trend in approximate average Al content with variation in cooling rate. From a petrogenetic perspective, it is not clear which end of the line the arrow-head should be on.

several other phases, often including ellipsoidal voids. The host pyroxene surrounding them is usually enriched in Fe, Ti, and Al, and depleted in Ca. Occasionally, the boundary between the Fe-enriched pyroxene surrounding the inclusion and the “normal” host pyroxene has a shape that looks crystallographically controlled (Fig. 3D). We suggest that, in addition to the minerals actually enclosed in melt, the Fe-rich wall pyroxene also grew from the trapped melt.

It is clear from Figs. 3A and 3B that these inclusions are concentrated in the Al-rich portions of the crystal. For example, the lower left portion of the large pyroxene crystal is free of inclusions in both the transmitted light image and the Al map. This is also true for the upper right portion of the crystal.

**Discussion:** The above observations lead to many questions: What is the origin of the complex Al zoning pattern. Why do most nakhlites have a bimodal distribution of Al contents? Why do the most rapidly cooled samples have the most Al-rich and most homogeneous pyroxenes? Is the Al zoning inherited from the magma chamber, and, if so, why would it correlate with cooling rate? Why are the melt inclusions concentrated in the Al-rich regions of the pyroxenes? Could the Al-rich portions of the pyroxenes have formed at greater depth, and then been more susceptible to fracture and melt infiltration during adiabatic decompression during eruption? Alternatively, could the Al-rich portions have grown more rapidly and thus trapped more melt? Is the Al zoning really a primary feature? If so, this would require that the crystals grew in a chaotic, skeletal fashion, or else had some sort of unusual sector

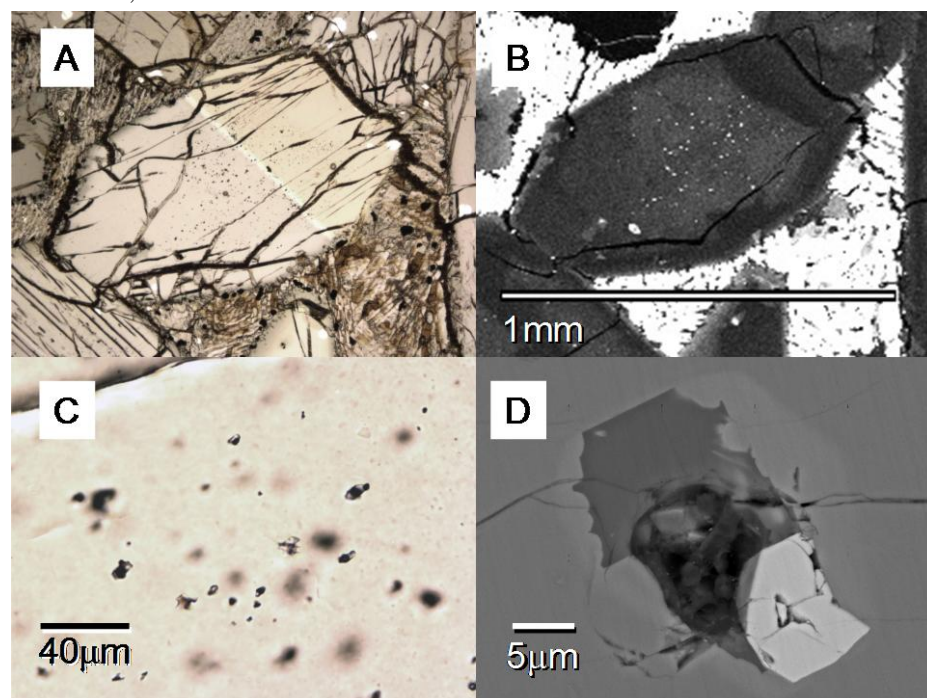
zoning.

Alternatively, could the zoning (and associated inclusions) be the result of post-eruptive alteration? In that case, one must ask which type of pyroxene, bimodal and low-Al or homogeneous and high-Al, represents the primary pyroxene. Conventional wisdom might have it that because MIL cooled so quickly that its intercumulus melt quenched to glass, there could be little opportunity for modification of its pyroxenes after emplacement. Extending that argument, one might consider that the least aluminous pyroxenes, the ones that were most slowly cooled, might have been modified to low-Al compositions during cooling. The problem with this notion is that diffusion rates are so slow in pyroxene that even with slow cooling there would be inadequate time to modify the Al content of the pyroxene.

It is not yet clear how NWA998 fits into the simple pattern shown in Fig. 2 (see our companion abstract [8]). Initially, it appears to be slowly cooled yet have high-Al pyroxenes, contrary to the current pattern.

We currently have many more questions than answers. We intend to conduct controlled growth experiments to improve our understanding of zoning and melt inclusion entrapment.

**References:** [1] Treiman A. H. (2005) *Chemie de Erde*, 65, 203-296. [2] Mikouchi T. *et al.* (2003) *Antarct. Meteorite Res.*, 16, 34-57. [3] Mikouchi T. *et al.* (2005) LPSC 36, Abs #1944. [4] McKay G. and Mikouchi T. (2005) MAPS 40, A5335. [5] McKay G. (1993), *Meteoritics* 28, 395. [6] Varela M. *et al.* (2001) *Mineral. Petrol.* 71,155. [7] Stockstill K. *et al.* (2002) LPSC 23, Abs #1644. [8] Mikouchi T. *et al.* (2006) LPSC 37.



**Figure 3A.** Transmitted light view of Y593 pyroxene. Note dusty inclusions in center of grain and their absence in upper right and lower left portion of grain. **B.** Al map of same grain. Note overall Al zoning, with irregular Al-rich patch in center. The bright spots are Al-rich melt inclusions. **C.** Transmitted light view of inclusions. **D.** BSE image of inclusion showing glass, titanomagnetite, and an ellipsoidal void space that has unidentified phases along its internal margin. Note the Fe-enriched pyroxene bordering the inclusion.